

MeV Gamma-Ray Imaging Detector with micro-TPC

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Abstract

We propose a new imaging gamma-ray detector in the MeV region. By measuring the directions and energies of not only a scattered gamma ray but also a recoil electron, the direction of an incident gamma ray would be essentially reconstructed event by event. Furthermore, one of two measured (zenith and azimuth) angles of a recoil electron gives us an additional redundancy which enables us to reject the background events by kinematic constraints. In order to measure the track of a recoil electron, the micro Time Projection Chamber(μ -TPC) has been developed, which can measure the successive positions of the track of charged particles in a few hundred micron meter pitch. The μ -TPC consists of the new type of a gas proportional chamber: micro P*IX*el gas Chamber (μ -PIC) which is one of wireless gas chambers and expected to be robust and stable. Using this μ -TPC and the Anger camera for the detection of a scattered gamma ray, we have obtained the first gamma-ray image by the full reconstruction of the direction of gamma rays event by event.

Key words: , gamma-ray telescopes, gas detector, nuclear gamma rays,
gamma-rays astronomical observations,
PACS: 95.55.K, 95.85.K, 29.30.K, 29.40.M

1 Introduction:

Nowadays gamma-ray astronomy has become a very promising field of astronomy. However the MeV region of gamma rays is still uncultivated, although this region would surely show us new aspects of high energy phenomena in the universe. In fact, COMPTEL in Compton Gamma-Ray Observatory had observed for 9 years, and found about 30 celestial objects emitting MeV gamma rays(Schönfelder et al. , 2000). However, taking into account of more than two hundreds discoveries of GeV gamma-ray emitters by EGRET, it is expected

that more than a hundred celestial objects would be detected in the MeV region. This is almost due to the nonexistence of a reliable imaging method of MeV gamma rays scattered via Compton process in the matter.

Recently multi-Compton telescopes have eagerly been studied as a next generation of the detector launched in satellites(Kurfess , 2003). Here we propose a new imaging detector of MeV gamma rays measuring both the directions and energies of not only a scattered gamma ray but also a recoil electron, which enables us to reconstruct the direction of an incident gamma ray event by event. Figure 1 shows the schematic view of the planned detector based on this concept for a balloon-borne experiment, which consists of a 30cm cubic μ -TPC surrounded by a scintillation pixel detector. Also it is pointed out that one of two measured angles of a recoil electron gives us an additional redundancy which enables us to reject almost all the background events by the kinematic constraint.

Classical Compton telescopes measure the energies of both the scattered gamma ray and recoil electron, and one direction of the scattered gamma ray. Since this method losses the direction of the recoil electron, only one angle (ϕ) of the incident gamma ray can be determined. Furthermore there remains no redundancy to reject the background. In the MeV region, not only strong celestial diffuse gamma rays but also the huge background gamma rays from the albedo and the satellite itself by irradiation of cosmic rays come to the detector in space. In addition, internal radioactivities in the detector emit both gamma rays and beta decay electrons faking a real gamma ray in Compton detectors. Good reviews of the analysis for the background in COMPTEL were presented in this workshop(Schönfelder , 2003; Ryan , 2003). In order to achieve a sensitivity ten times better than COMPTEL, another powerful method for the background rejection seems to be inevitable for the next MeV gamma-ray imaging detector.

Here we introduce the new type of a gamma-ray imaging detector based on a wireless gas detector, and the results of its performance study are presented.

2 Detector

In order to obtain a 3-D track of a recoil electron, μ -TPC has been developed, which measures the successive positions of the track of charged particles in a few hundred micron meter pitch(Nagayoshi et al. , 2002; Miuchi et al. , 2003). This μ -TPC consists of the new type of a gas proportional chamber: μ -PIC which is one of wireless gas chambers and expected to be more robust and stable than micro strip gas chambers(Ochi et al. , 2001, 2002). At the first stage, we have developed a prototype μ -TPC having a detection volume of 10

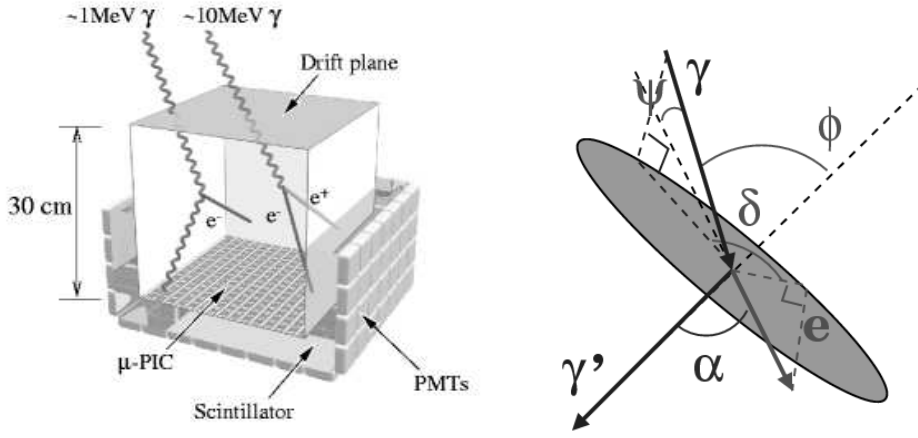


Fig. 1. Schematic view of the planned detector for a balloon-borne experiment, which consists of a 30cm cubic μ -TPC surrounded by a scintillation pixel detector(left figure). In the right figure, definitions of the angles are shown.

$\times 10 \times 8 \text{ cm}^3$. All results mentioned here are obtained using this prototype detector.

We briefly mention the essential features of μ -PIC and μ -TPC. μ -PIC is a gaseous two-dimensional position-sensitive detector manufactured by the printed circuit board(PCB) technology. A schematic structure of the μ -PIC is shown in Fig.2. With the PC-board technology, large area detectors would be mass-produced with low costs. The pixel pitch of the μ -PIC is $400 \mu\text{m}$. μ -TPC was stably operated with the gas gain of ~ 3000 for more than 1000 hours. Each signal of an anode and a cathode is amplified and shaped with 80ns time constant and discriminated. For the energy measurement, analog signals of the amplifier connected to the cathode strips are summed 32 to one on the amplifier board, and its waveforms are recorded by the 8-channel 100 MHz flash ADC (FADC). Energy resolution of $\sim 30\%$ (FWHM) was obtained for 5.9 keV X-rays. Discriminated pulse (LVDS-level pulse) are fed to the encoder board comprising five FPGA chips. Here hit signals on the μ -PIC are synchronized with an internal clock (20 MHz), and their positions were recorded successively at an anode-cathode coincidence within one clock. Therefore tilted particle track in the drift volume can be recorded as successive hit points as shown in Fig.3. In this way, we realize both three-dimensional tracking and spectroscopy of the charged particles with μ -TPC(Kubo et al. , 2003). Three-dimensional spatial resolution of $260 \mu\text{m}$ was measured by the irradiation with proton beams. This spatial resolution is restricted by the clock rate of the electronics and the drift velocity in μ -TPC ($\sim 5\text{cm}$ per $1\mu\text{s}$). All the test on the μ -TPC described here were carried out using the Ar-C₂H₆ gas mixture with a normal pressure.

Fig. 3 shows the examples of obtained tracks of low energy proton (large dE/dx) and β -decay electron (near Minimum Ionizing Particle: MIP), which

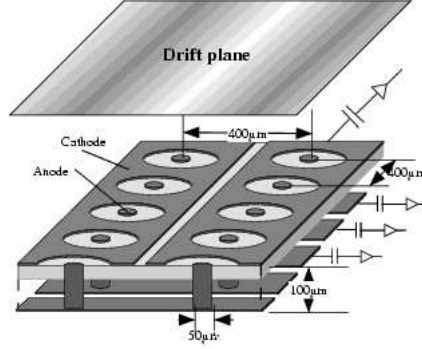
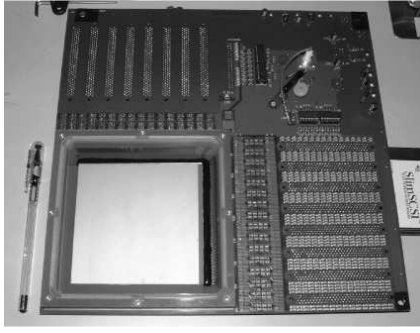


Fig. 2. Top view of the 10cm square 2-D μ -PIC attached on a PC-board (left), and schematic view of the structure of μ -PIC (right).

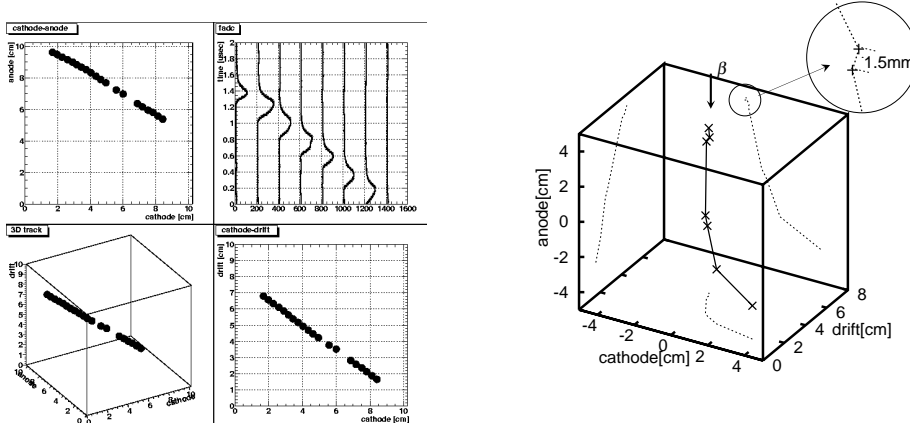


Fig. 3. Typical track of a 0.8 GeV proton (left) and low energy electron emitted from β decay (right) reconstructed by μ -TPC.

indicates that more gain (~ 10000 , three times of the present gain) is needed for the sufficient detection of MIPs. The detection efficiency for MIPs is $\sim 10\%$ when requiring at least 5 hit points in one track of MIP. Now the electrode structure of μ PIC is being improved.

3 Imaging Performance

Scattered gamma rays are detected by the Anger scintillation camera consisting of $10 \times 10 \times 2.5 \text{ cm}^3$ NaI(Tl) plate and 5×5 3/4-inch phototube array (Fig.4). Energy and position resolutions of the Anger camera for 662 keV gamma ray are 9 % and 7.5mm at FWHM, respectively. Our gamma-ray imaging detector consists of μ -TPC and the Anger camera, as shown in Fig.4, where a gamma-ray source and Anger camera are placed 5cm behind the μ -TPC and 10cm at the front of the μ -TPC, respectively. We examined the imaging performance of the prototype detector with three gamma-ray energies of ^{133}Ba (356keV), ^{22}Na (511keV), and ^{137}Cs (662 keV). In the off-line analysis

we required following constraints; the minimum number of hit positions of the track in μ -TPC (at least five points per track), hit positions within fiducial volumes of both μ -TPC and the Anger camera, a loose requirement of an energy deposit in the Anger camera, and the simple kinematic constraint for α angle between the scattered gamma ray and recoil electron. Since the energy calibration of the μ -TPC was not so accurate to sum with the energy of the Anger camera, an initial energy of gamma rays was treated as a known parameter.

Figure 5 shows the distributions of two angles of ϕ and δ obtained by the event reconstruction for ^{137}Cs (662 keV). Here we used only the events in which both a scattered gamma ray and a recoil electron were detected, and hence we could determine the direction of an incident gamma ray event by event. We point out that we did not use any imaging method such as a maximum entropy method. Resultant angular resolutions are 20 and 25 degrees at RMS, respectively. Also in Fig. 5, the reconstructed images of the gamma-ray source are presented, where the source position was shifted about 40 degrees in the measurement, and the reconstructed image was obviously also moved by this shift as shown in the bottom figure. The angular resolution of ϕ , which is used in classical Compton telescopes, is limited by the position and energy resolutions of both detectors, and our results looks near the expected one from the energy and position resolutions of the Anger camera. That of δ is limited by the multiple scattering of the recoil electron and tracking resolution of μ -TPC. Obtained resolution of 25 degree is about three times worse than the simulated one due to the insufficient gain of μ -PIC.

Thus we have achieved the full reconstruction of Compton process event by event and obtained the true gamma-ray image although the resolution of an image was still primitive. Also we point out that a gas detector having a fine tracking resolution such as μ -TPC makes it possible to detect lower energy gamma rays from ~ 200 keV.

4 Simulation study for the balloon-borne experiment

We are developing this MeV gamma-ray imaging detector for an all-sky survey in the MeV region, and as a first step we plan to perform a balloon-borne experiment launching a 30cm cubic μ -TPC surrounded by a scintillation pixel detector (5mm square pixel assumed). Simulated performances for this detector are described in detail elsewhere(Orito et al. , 2003). For example, figure 6 shows the expected two angular resolutions as a function of the gamma-ray energy. This simulation study shows that a 30cm-cubic detector has a detection efficiency of ~ 1 % above 200 keV. Assuming this efficiency with the use of 1.5 bar pressured Xe gas, about one thousand gamma rays from the Crab

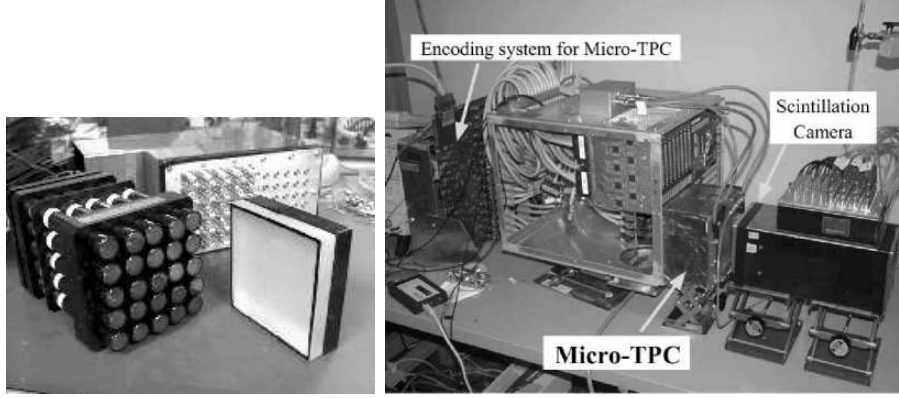


Fig. 4. Photograph of the NaI(Tl) scintillator and the array of 3/4-inch PMTs(left), and side view of the set-up for the measurement of gamma-ray images, where a gamma-ray source and Anger camera are placed 5cm behind the μ -TPC and 10cm at the front of the μ -TPC, respectively(right).

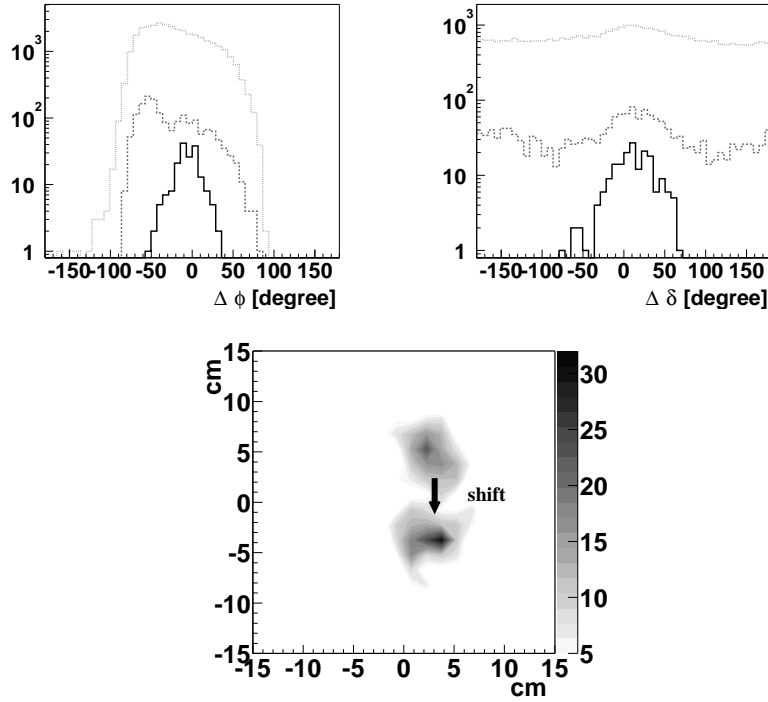


Fig. 5. Angular resolutions of two angles of incident gamma rays, ϕ (top-left figure) and δ (top-right figure), where dotted-line, dashed-line and solid-one are obtained for raw data, after applying fiducial and energy cuts, and also after applying all-cuts, respectively. Also reconstructed images are plotted in the bottom figure, where the source position was shifted about 40 degrees in the measurement, and the reconstructed image was obviously also moved by this shift as shown in the bottom figure.

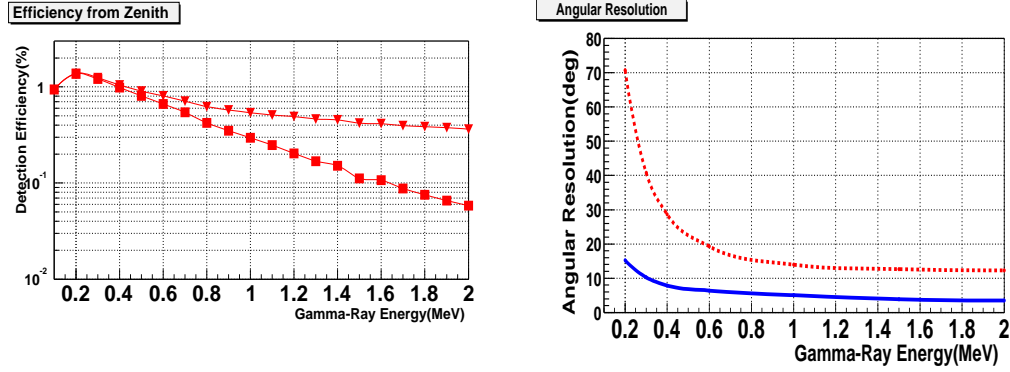


Fig. 6. Simulated detection efficiency (square plot in the left figure) and angular resolutions of two incident angles, δ and ϕ (dotted and solid lines in the right figure) as a function of the incident gamma-ray energy, where 1.5 bar pressured Xe gas in the μ -TPC is assumed. Although Ar-C₂H₆ mixture gas was used here for its convenience, pressured Xe gas will be needed to obtain the high detection efficiency for real observations. In the left figure, triangle plots indicate the efficiency when the energy of an electron passing through the vessel were obtained using a thin silicon pad detector located out of the field cage of the TPC.

in the energy region from 200 keV are expected to be detected by 6 hours observation.

This work is supported by a Grant-in-Aid in Scientific Research of the Japan Ministry of Education, Culture, Science, Sports and Technology, and Ground Research Announcement for Space Utilization promoted by Japan Space Forum.

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